BICT 14th EAI International Conference on Bio-inspired Information and Communications Technologies

Quantum Internet

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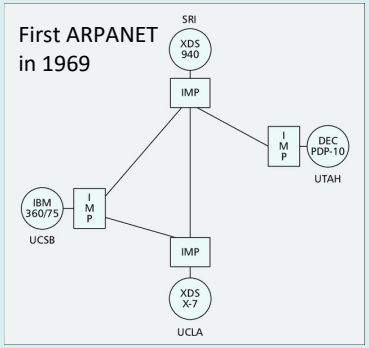
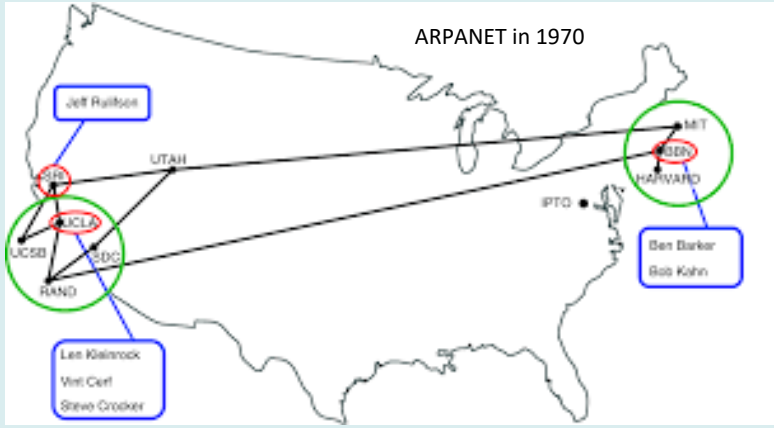
Evolution of the Internet

- ARPANET – 1969~1989, predecessor of Internet; network that can still function after portions are removed/destroyed
- Connects computers utilized by humans for exchanging files, remote host access, sending emails, etc.



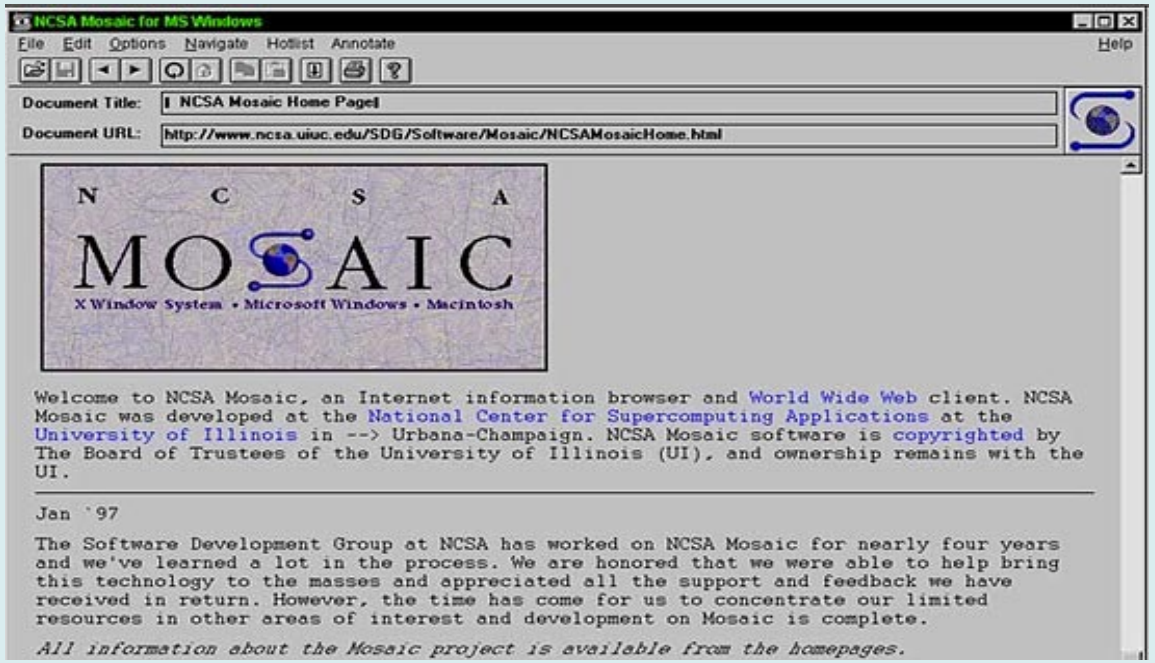
Source: IEEE Communications Magazine (2010)



Source: IEEE Computer Magazine (2019)

Evolution of the Internet

- World Wide Web transformed the Internet !!!
- Primary source of information, services and applications



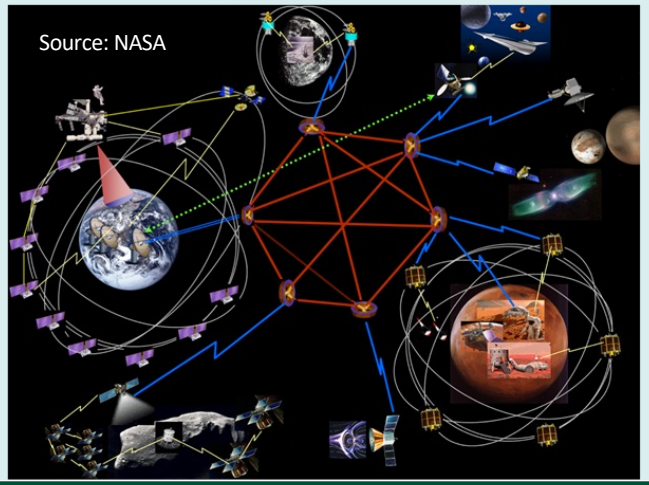
Evolution of the Internet

- Now, machines and things are taking over the Internet…

  By 2030, close to 30 billion IoT device vs. 10 billion non-IoT device connections worldwide – statista

- Interplanetary Internet

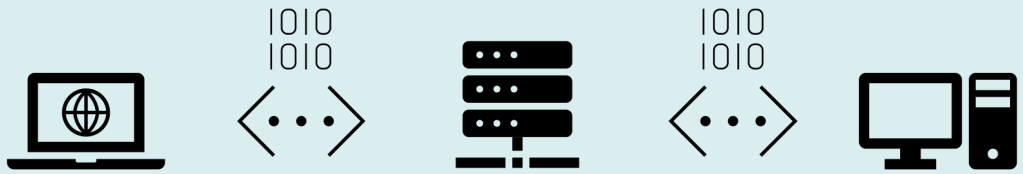
  Computer network in space



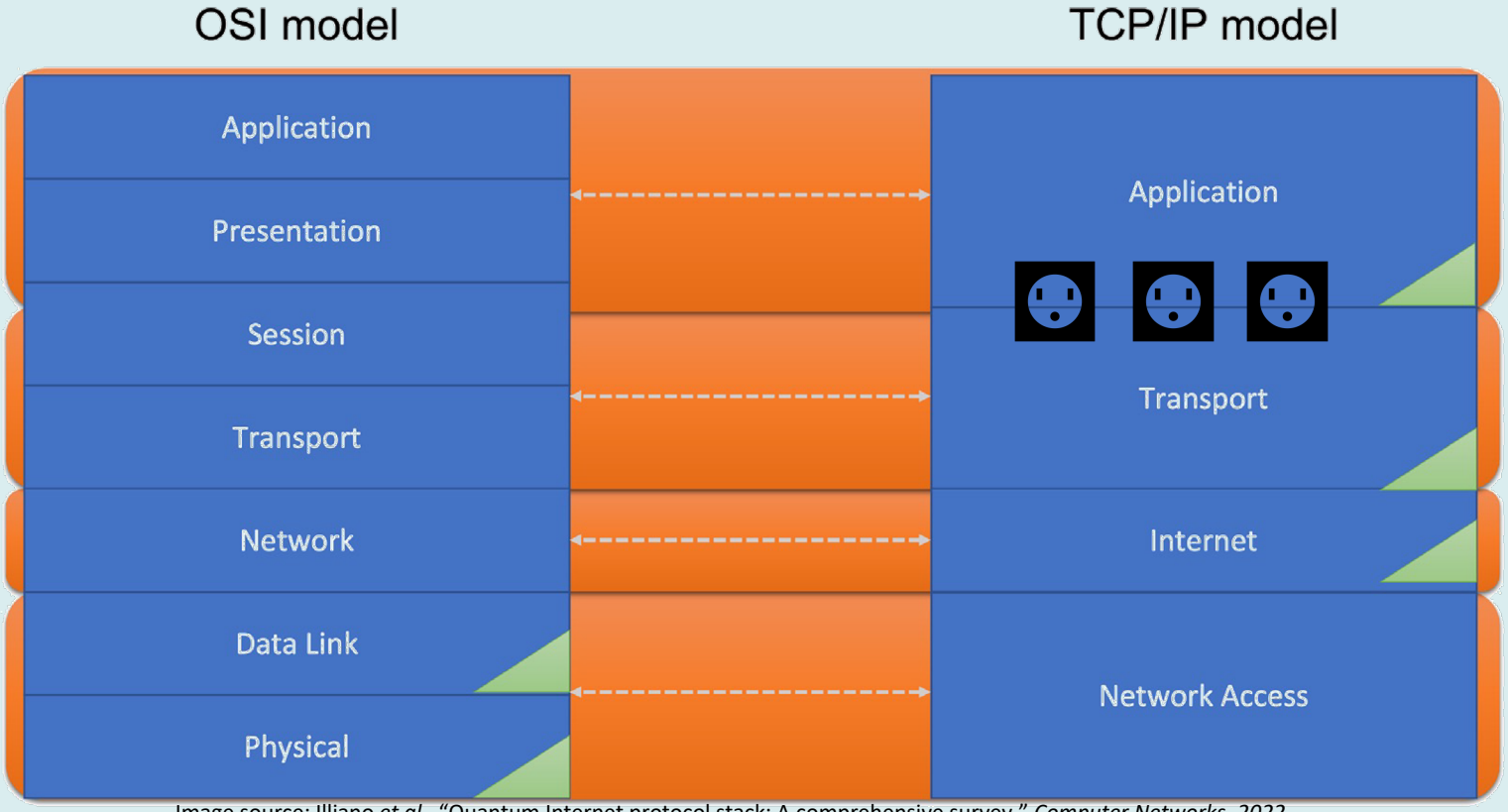
- **Still classical networks**

Classical Computing & Networking

- Classical computers
  - Store information in bits, either “0” or “1”
  - Deterministic & measurements do not change state
  - Two bits – 00, 01, 10 and 11
- Classical networks



Building Block of the Internet



network sockets

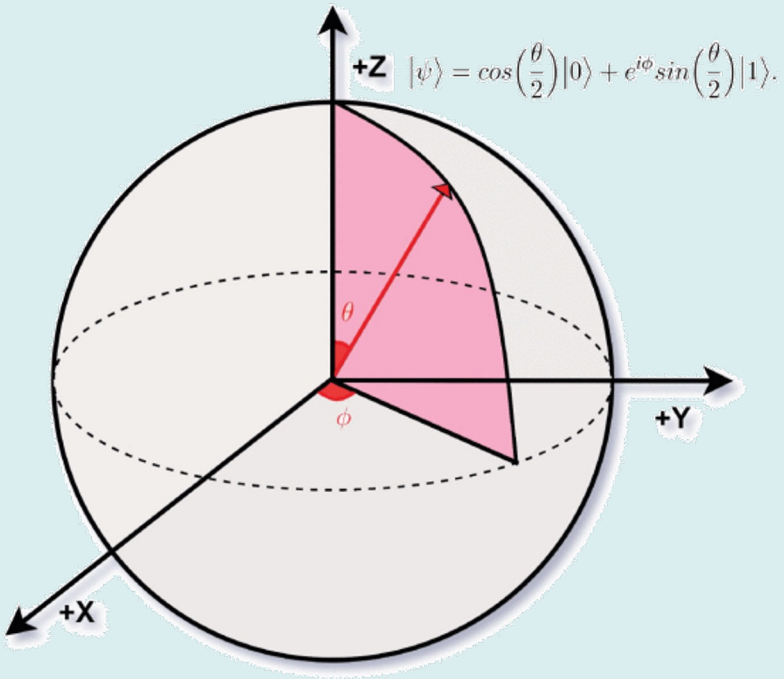
Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Quantum Basics

Quantum bits, **qubits** – superposition of "0" or "1"

- State of A, one-qubit system
  $|A\rangle = a_0|0\rangle + a_1|1\rangle$ where $a_0, a_1 \in \mathbb{C}$
  a_0, a_1 – probability amplitudes to measure "0" or "1"
- Probability of measuring $|0\rangle$ is $|a_0|^2$ and $|1\rangle$ is $|a_1|^2$, and $|a_0|^2 + |a_1|^2 = 1$
- Two qubit example
  $|A\rangle = a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle$
  where $|a_{00}|^2 + |a_{01}|^2 + |a_{10}|^2 + |a_{11}|^2 = 1$

Quantum Basics



How to make qubits?

- Non-solid state
  - Photons
  - Trapped ions
- Solid state
  - Superconductors
  - Nitrogen-Vacancy-Centres or NV-Centres in diamond
  - Semiconductor Quantum Dots
    - quantum dot → single electron transistor, very similar to classical field effect transistor

Quantum Basics

No-cloning theorem

- Qubit can be directly transmitted to a remote node via an optical fiber link or free space optical
- But, if photon is lost due to attenuation or it is corrupted by noise,
  - it cannot be recovered by some form of measurement or by re-transmitting a copy of the original information.
  - classical communication / networking approaches are NOT applicable!!!

Quantum Basics

Entanglement and *Teleportation*

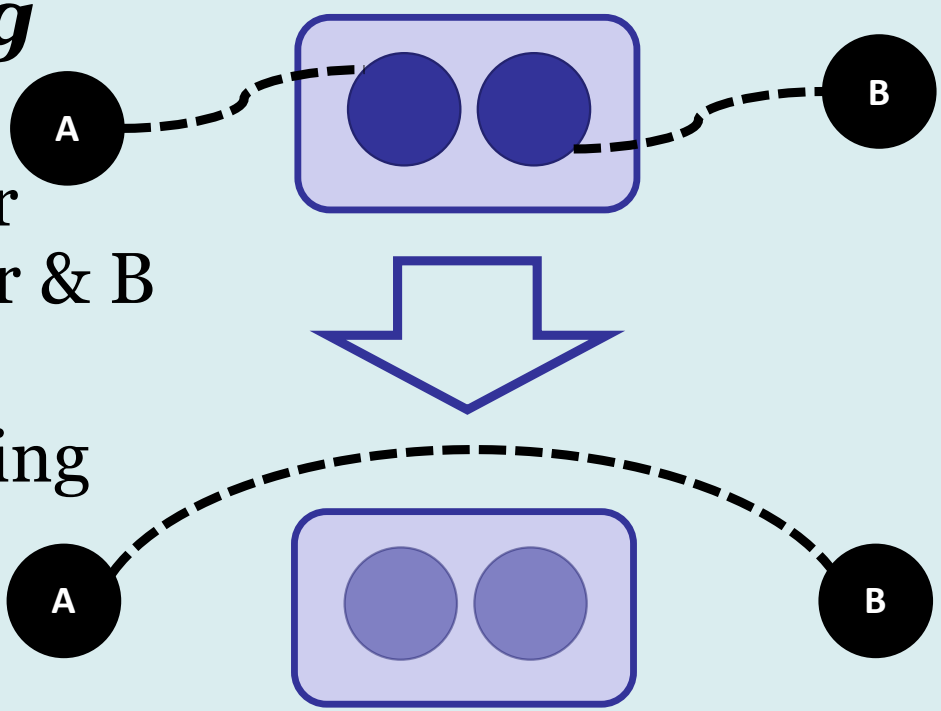
- Suppose two qubits A and B are “entangled”
- If A is measured, then B will immediately have the same state as A
- No matter how far apart A and B are !!!

➢ How to entangle the two qubits on different nodes?

Quantum Basics

Entanglement swapping

- Generate entanglements between qubits in A & repeater and between qubits in repeater & B
- Entanglement swap between qubits in repeater → two existing pairs of entanglement destroyed but new entanglement created



Quantum Internet

- *Global network interconnecting heterogeneous quantum networks, able to transmit qubits and to generate and distribute entangled states*
- Sits side-by-side with classical internet
- Supports distributed quantum application protocols with highest fidelity & efficiency

Quantum Internet

- Application classes as defined by Quantum Internet Research Group (QIRG) of Internet Engineering Task Force (IETF) :
  - quantum cryptography – quantum key distribution, fast Byzantine negotiation (consensus/mining in blockchains), quantum money (suggested in 1970s)
  - quantum sensing – network clock synchronization, extending baseline of telescopes
  - quantum computing – distributed quantum computing, secure with privacy preservation

Internet Protocol Stack

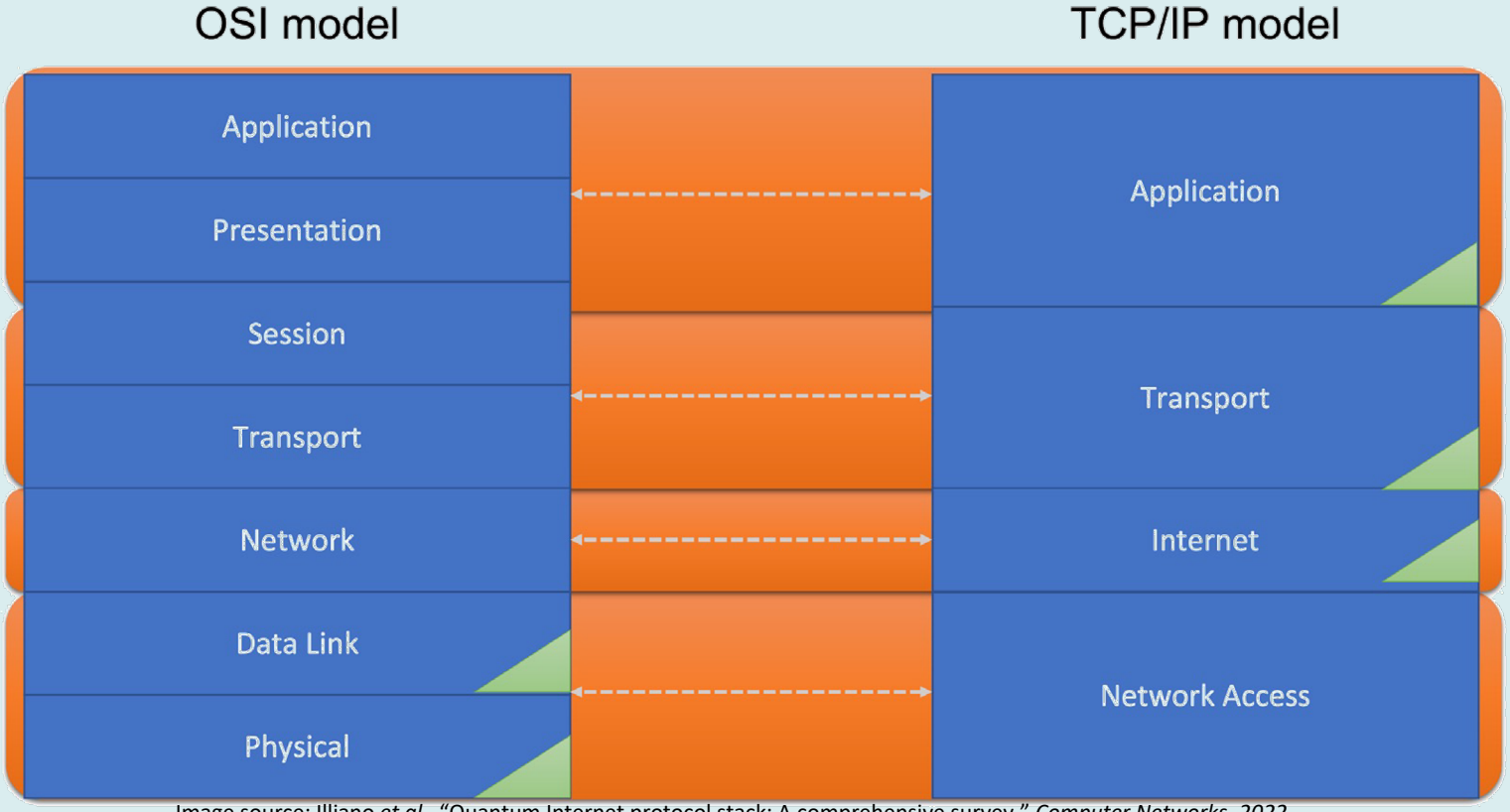


Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Quantum Internet Protocol Stack

"by simply replacing or extending some classical protocols to their quantum counterpart, without any global modification of the overall protocol stack. Unfortunately, this approach is doomed to fail…"

– Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks*, 2022.

Quantum Internet Protocol Stacks

Proposals:

- Van Meter *et al.*
- Wehner *et al.*
- Dür *et al.*
- others

Quantum Stack by Van Meter *et al.*

- Started in 2009

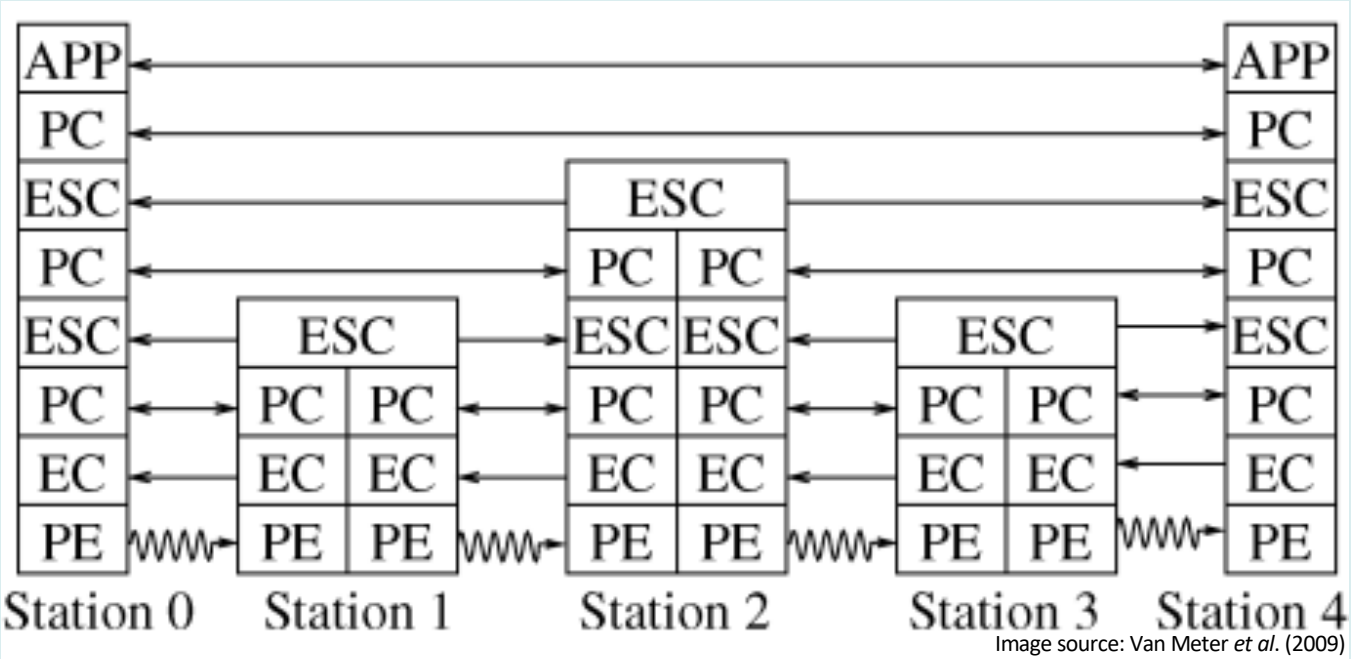


Image source: Van Meter *et al.* (2009)

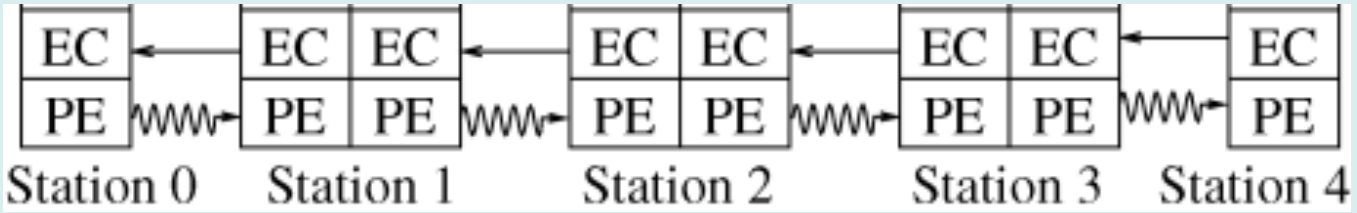
wavy lines - optical pulses → the qubits straight lines - classical communication.

APP – Application
PC – Purification Control
ESC – Entanglement Swapping Control
EC – Entanglement Control
PE –Physical Entanglement

Quantum Stack by Van Meter *et al.*

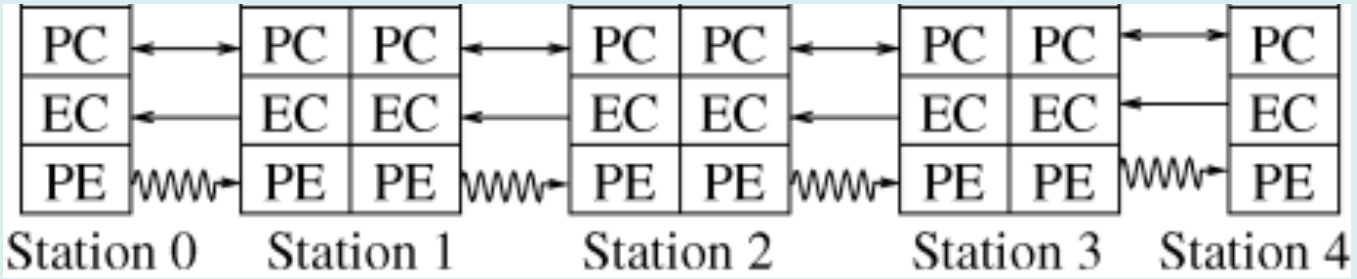
Physical Entanglement / Entanglement Control

- Use strong laser pulses or single photons to create entanglement between two qubits on different nodes
- Measure properties of the laser pulses to assess whether the attempt was successful or not
- Send (classical) ACK/NACK to report outcome



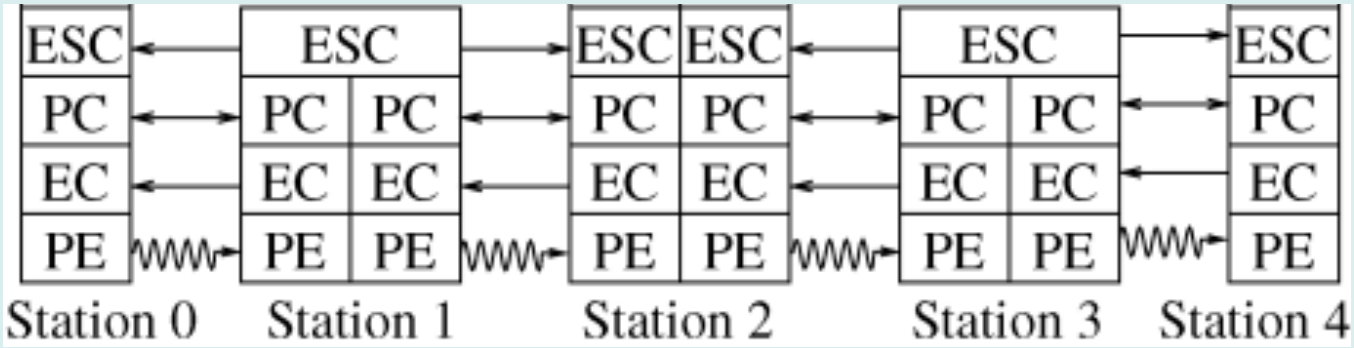
Quantum Stack by Van Meter *et al.*

- Purification Control
  - Quantum purification algorithm to improve the quality (fidelity) of the entangled pairs
  - Scheduling of the entangled pairs to be purified



Quantum Stack by Van Meter *et al.*

- Entanglement Swapping Control
  - Performs entanglement swapping
  - Informs end nodes on outcome of swapping operation, which is probabilistic
  - Repeat PC & ESC until desired e2e node pairs are entangled.



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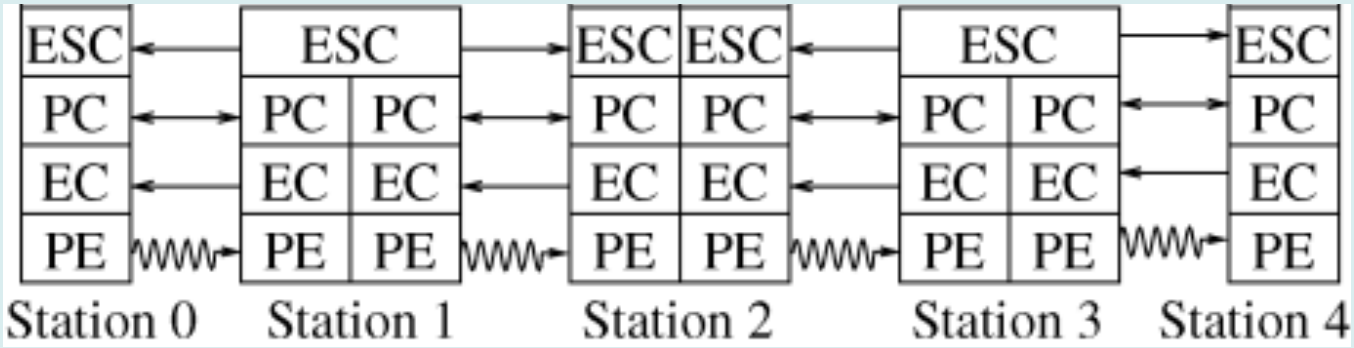

Quantum Stack by Van Meter *et al.*

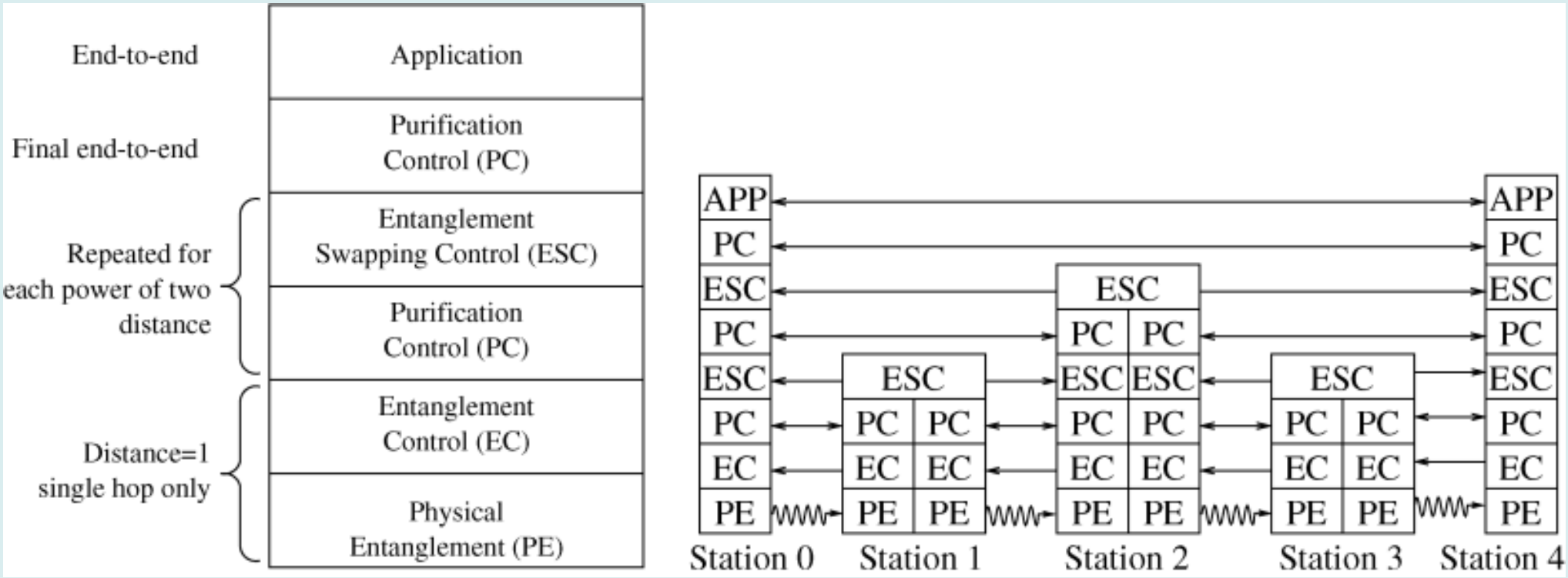

Image source: Van Meter *et al.*, "System Design for a Long-Line Quantum Repeater," *IEEE Trans on Networking*, 2009.

Quantum Stack by Van Meter *et al.*

Quantum Recursive Network Architecture

- Proposed in 2011
- Recursive executions of PC/ESC

  → *single individual link represented by a high-fidelity entanglement shared between source and destination nodes*

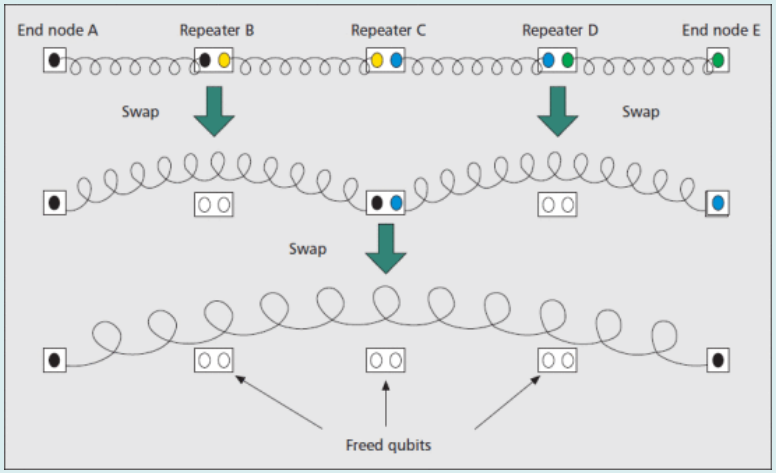

Image source: Van Meter *et al*. "Designing quantum repeater networks," *IEEE Communications Magazine*, 2013.

- Like *network of networks* → the Internet

Quantum Stack by Van Meter *et al.*

- Entanglement distribution among quantum nodes requires *virtual/physical network topology* and *coordination among nodes*
- In 2019, proposed a *bootstrap protocol* for:
  - supporting coordinated autonomous decision-making in quantum operations over a network
  - quantifying achievable fidelity, accounting for classical control messages

Quantum Stack by Van Meter *et al.*

Contributed to ***Quantum Sockets*** as part of IRTF efforts; RFC9340 published in March 2023:

- Application types:
  1) Exploit entangled state without consuming them
  2) Consume entangled qubits directly by measuring the qubits immediately after execution
- Manage synchronous/asynchronous coordination required by applications running at a node

Quantum Internet Protocol Stacks

Proposals:

- Van Meter *et al.*
- Wehner *et al.*
- Dür *et al.*
- others

Quantum Stack by Wehner *et al.*

- Layered model for quantum networks, based on *bipartite entanglement*
- Physical and link layer functionalities and protocols
- For NV centres in diamond
- later revised to be underlying platform independent

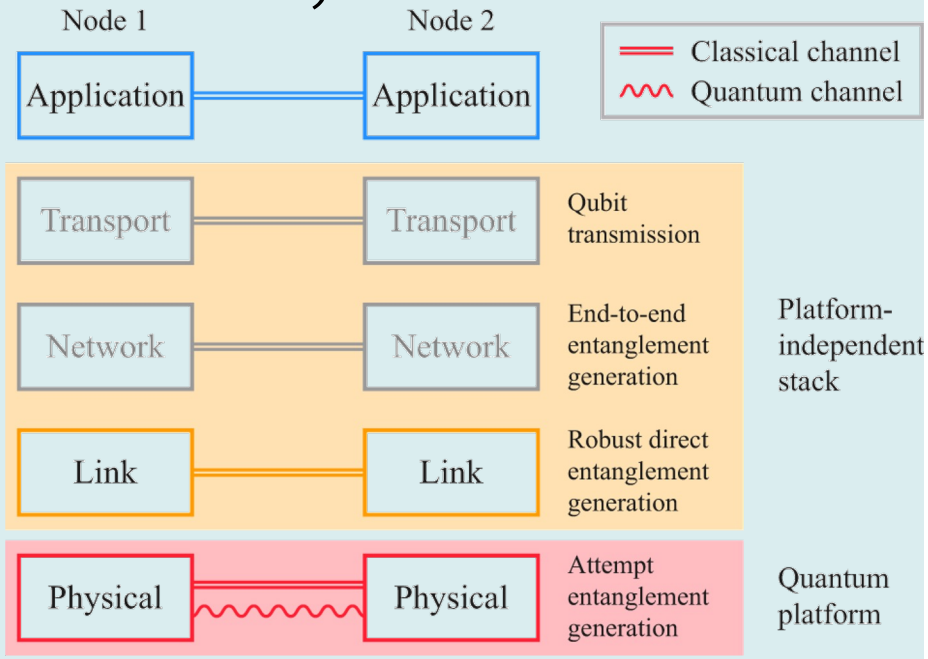

Image source: Pompili *et al.*, *npj Quantum Inf* , 2022.

Quantum Stack by Wehner *et al.*

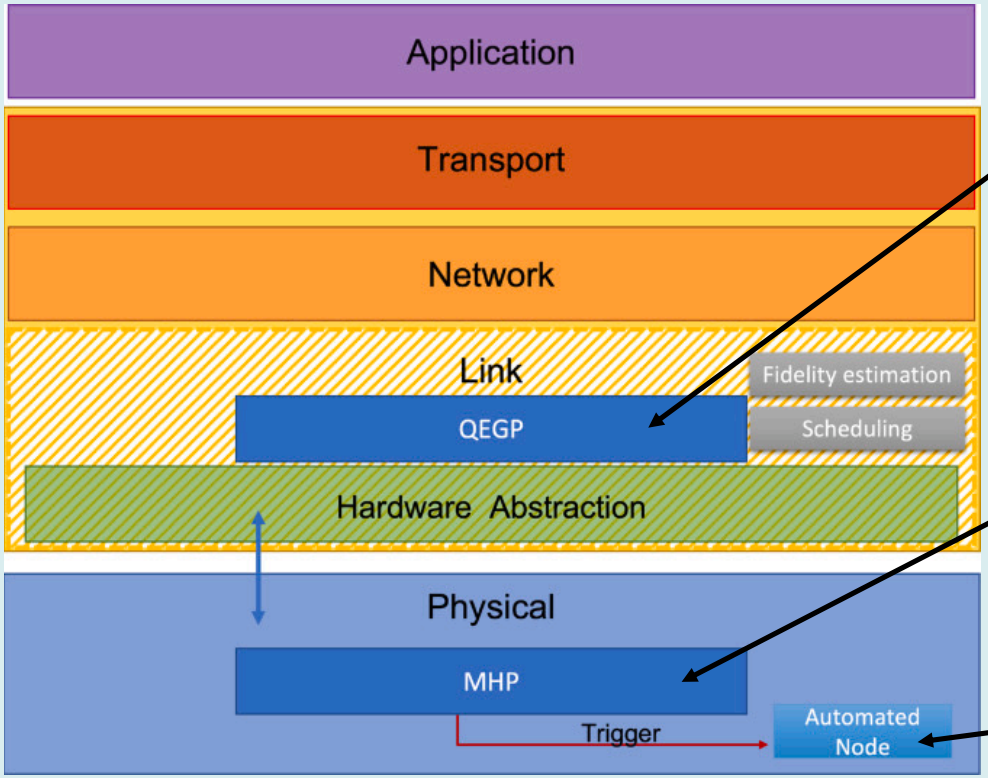

Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Gets inputs from upper layers:
- remote node ID, #entangled pairs, minimum fidelity, request type, measurement basis, etc.

Instructs lower layer protocols through Hardware Abstraction Layer

- Coordinates automated nodes;
- Polls the link layer to determine whether entanglement generation is required or not in a given time slot.

- Devices triggered to generate entanglement.

Quantum Internet Protocol Stacks

Proposals:

- Van Meter *et al.*
- Wehner *et al.*
- Dür *et al.*
- others

Quantum Stack by Dür *et al.*

- Uses multi-partite entangled states, manipulated to fulfill the node requests
- Three phases of network evolution:
  - *dynamic* - entanglement is generated & distributed among the nodes
  - *static* - nodes share some entangled quantum states
  - *adaptive* - entangled states are manipulated to either fulfill the nodes requests or deal with failures

Quantum Stack by Dür *et al.*

- ***Physical layer***
  - free space optical or optical-fibre channels, for connecting devices
  - direct transmission of quantum particles encoding the informational qubits, without any error correction or entanglement purification
- ***Connectivity layer*** - establishes long-distance entanglement through quantum repeaters

Quantum Stack by Dür *et al.*

- ***Link layer*** – provides services based on phase
  - *dynamic* phase - generating multipartite entangled states, distributed among the nodes of the network
  - *adaptive* phase – generating arbitrary graph states between clients, according to their requests
- ***Network layer*** – establishing inter-network entanglement, entangling nodes belonging to different quantum networks, through network devices called *quantum routers*

Quantum Stacks Comparison

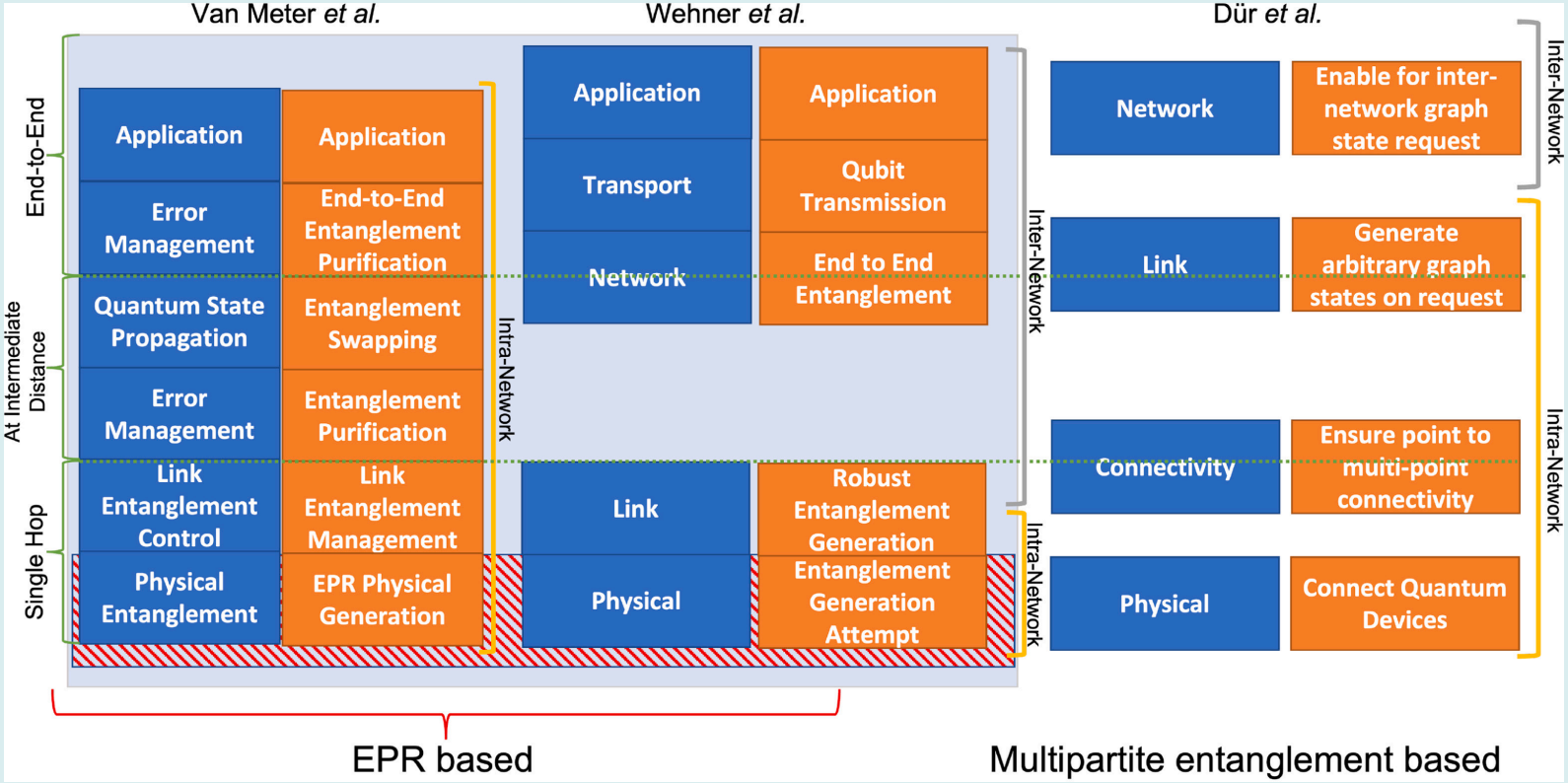

Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Open issues and research directions

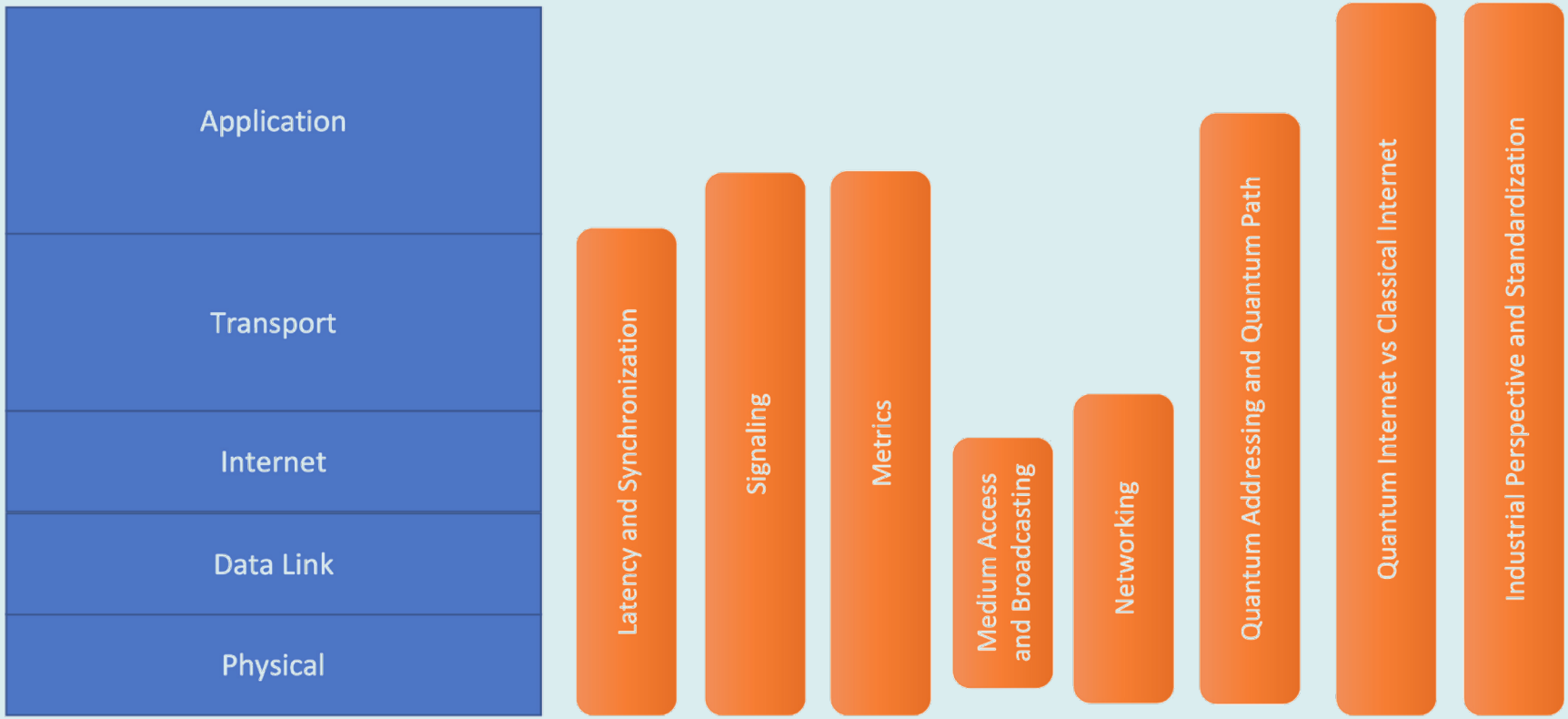

Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Open Issues – Standardization

- Lack of unified quantum internet protocol stack
- International projects and standardization efforts (e.g., in ITU, IETF, IEEE, GSMA, ETSI) for:
  - architectures, interfaces and protocols
  - interoperability between quantum networks
  - seamless interworking with current infrastructures

Open Issues – Signaling vs Data

- Coordination is critical and exchange of control information still relies on classical internet
- Telecommunication networks have dedicated signaling channels
- Classical internet carries both data and signaling in-band
- Entanglement needs qubits on nodes → less qubits on nodes for quantum data

Open Issues – Medium Access

- How to arbitrate / coordinate access to virtual link → utilization of entanglement as resource?
- Two or more nodes share an entanglement
  - Which node to use and when?
  - Entanglement Access Control (EAC) protocol
  - Much harder with multiparty entanglement
- No-broadcasting theorem – unknown quantum state cannot be broadcast to two / more receivers

Open Issues – Networking

- Given *no-cloning* theorem, how to provide basic networking functionalities – neighbour discovery, path discovery, forwarding and routing
- Entanglement-based communications vs direct transmission
- Entanglement generation and entanglement-aware routing
- Error control and correction for reliability

Acknowledgements

- Dr Del Rajan, PhD.
  for introducing me to quantum networking
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  for James Cook Research Fellowship to conduct fulltime research for 2 years on *Quantum Networking Protocols and Algorithms*

Questions???

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https://ecs.wgtn.ac.nz/Groups/WiNe/WirelessNetworksResearchGroup